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भारतीय मानक

उच्च-वोल्टता दिष्ट धारा (एच.वी.डी.सी.) पावर प्रेषण हेतु वोल्टेज चलित परिवर्तक (वी.एस.सी.) वाल्व — विद्युत परीक्षण

Indian Standard

VOLTAGE SOURCED CONVERTER (VSC) VALVES FOR HIGH-VOLTAGE DIRECT CURRENT (HVDC) POWER TRANSMISSION — ELECTRICAL TESTING

ICS 29.200; 29.240

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NATIONAL FOREWORD

This Indian Standard which is identical with IEC 62501 : 2009 'Voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) power transmission — Electrical testing' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the HVDC Power Systems Sectional Committee and approval of the Electrotechnical Division Council.

The text of IEC Standard has been approved as suitable for publication as an Indian Standard without deviations. Certain terminology and conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.
b) Comma (,) has been used as a decimal marker, while in Indian Standards the current practice is to use a point (.) as the decimal marker.

In this adopted standard, references appear to certain International Standards for which Indian Standards also exist. The corresponding Indian Standards, which are to be substituted in their respective places are listed below along with their degree of equivalence for the editions indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60060 (All parts) High-voltage test techniques	IS 2071 (All parts) High voltage test techniques	Technically Equivalent
IEC 60060-1 : 1989 High-voltage test techniques — Part 1: General definitions and test requirements	IS 2071 (Part 1) : 1993 High voltage test techniques: Part 1 General definitions and test requirements (*second revision*)	Identical
IEC 60071-1 : 2006 Insulation co-ordination — Part 1: Definitions, principles and rules	IS/IEC 60071-1 : 2006 Insulation co-ordination: Part 1 Definitions, principles and rules	do
IEC 60700-1 : 1998 Thyristor valves for high voltage direct current (HVDC) power transmission — Part 1: Electrical testing	IS 14911 (Part 1) : 2001 Thyristor valves for high voltage direct current (HVDC) power transmission: Part 1 Electrical testing	do
ISO/IEC 17025 : 2005 General requirements for the competence of testing and calibration laboratories	IS/ISO/IEC 17025 : 2005 General requirements for the competence of testing and calibration laboratories	do

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

Indian Standard

VOLTAGE SOURCED CONVERTER (VSC) VALVES FOR HIGH-VOLTAGE DIRECT CURRENT (HVDC) POWER TRANSMISSION — ELECTRICAL TESTING

1 Scope

This International Standard applies to self-commutated converter valves, for use in a three-phase bridge voltage sourced converter (VSC) for high voltage d.c. power transmission or as part of a back-to-back link. It is restricted to electrical type and production tests.

The tests specified in this standard are based on air insulated valves. For other types of valves, the test requirements and acceptance criteria must be agreed.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60060 (all parts), *High-voltage test techniques*

IEC 60060-1:1989, *High-voltage test techniques – Part 1: General definitions and test requirements*

IEC 60071-1:2006, *Insulation co-ordination – Part 1: Definitions, principles and rules*

IEC 60700-1:1998, *Thyristor valves for high voltage direct current (HVDC) power transmission – Part 1: Electrical testing* 1)

Amendment 1(2003)
Amendment (2008)

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1 Insulation co-ordination terms

3.1.1

test withstand voltage
value of a test voltage of standard waveshape at which a new valve, with unimpaired integrity, does not show any disruptive discharge and meets all other acceptance criteria specified for the particular test, when subjected to a specified number of applications or a specified duration of the test voltage, under specified conditions

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1) There exists a consolidated edition 1.2 (2008) that comprises IEC 60700-1, Amendment 1 and Amendment 2.

3.1.2
internal insulation
air external to the components and insulating materials of the valve, but contained within the profile of the valve or multiple valve unit

3.1.3
external insulation
air between the external surface of the valve or multiple valve unit and its surroundings.

3.2 Power semiconductor terms

There are several types of controllable semiconductor switch device which can be used in VSC converters for HVDC. For convenience, the term IGBT is used throughout this standard to refer to the main, controllable, semiconductor switch device. However, the standard is equally applicable to other types of controllable semiconductor switch device.

3.2.1
insulated gate bipolar transistor
IGBT
a controllable switch with the capability to turn-on and turn-off a load current

An IGBT has three terminals: a gate terminal (G) and two load terminals emitter (E) and collector (C).

By applying appropriate gate to emitter voltages, the load current can be controlled, i.e. turned on and turned off.

3.2.2
free-wheeling diode
FWD
power semiconductor device with diode characteristic

A FWD has two terminals: an anode (A) and a cathode (K). The current through FWDs is in the opposite direction to the IGBT current.

FWDs are characterized by the capability to cope with high rates of decrease of current caused by the switching behaviour of the IGBT.

3.2.3
IGBT-diode pair
arrangement of IGBT and FWD connected in inverse parallel

3.3 Operating states

3.3.1 Operating state of an IGBT-diode pair

3.3.1.1
blocking state
the condition in which an IGBT-diode pair is turned off

In that state, the load current does not flow through the IGBT. However, a load current can flow through the diode as the diode is not controllable.

3.3.1.2
de-blocked state
the condition when the load current flows either through the IGBT or diode of an IGBT-diode pair depending on the load current direction

3.3.2 Operating state of converter

3.3.2.1
blocking state
a condition of the converter, in which a turn-off signal is applied to all IGBTs of the converter

Typically, the converter is in the blocking state condition after energization.

3.3.2.2
de-blocked state
a condition of the converter, in which turn-on signals are applied to IGBTs of the converter

3.3.2.3
valve protective blocking
means of protecting the valve or converter from excessive electrical stress by the emergency turn-off of all IGBTs in one or more valves

3.4 VSC construction terms

3.4.1
VSC phase unit
the equipment used to connect the two d.c. busbars to one a.c. terminal

3.4.2
VSC valve
complete controllable device assembly, which represents a functional unit as part of a VSC phase unit and characterized by switching actions of the power electronic devices upon control signals of the converter base electronics

NOTE Dependent on the converter topology, a valve can either have the function to act like a controllable switch or to act like a controllable voltage source.

3.4.3
diode valve
a semiconductor valve containing only diodes as the main semiconductor devices, which might be used in some VSC topologies

3.4.4
valve
VSC valve or diode valve according to the context

3.4.5
VSC valve level
part of a VSC valve comprising a controllable switch and an associated diode, or controllable switches and diodes connected in parallel, or controllable switches and diodes connected to a half bridge arrangement, together with their immediate auxiliaries, storage capacitor, if any

3.4.6
diode valve level
part of a diode valve composed of a diode and associated circuits and components, if any

3.4.7
redundant levels
the maximum number of VSC valve levels or diode valve levels in a valve that may be short-circuited externally or internally during service without affecting the safe operation of the valve as demonstrated by type tests, and which if and when exceeded, would require shutdown of the valve to replace the failed levels or acceptance of increased risk of failures

3.5 Valve structure terms

3.5.1

valve structure

physical structure holding the levels of a valve which is insulated to the appropriate voltage above earth potential

3.5.2

valve support

that part of the valve which mechanically supports and electrically insulates the active part of the valve from earth

NOTE A part of a valve which is clearly identifiable in a discrete form to be a valve support may not exist in all designs of valves.

3.5.3

multiple valve unit

MVU

mechanical arrangement of 2 or more valves or 1 or more VSC phase units sharing a common valve support

NOTE A MVU might not exist in all topologies and physical arrangement of converters.

3.5.4

valve section

electrical assembly defined for test purposes, comprising a number of VSC or diode valve levels and other components, which exhibits pro-rated electrical properties of a complete valve

The minimum number of VSC or diode valve levels allowed in a valve section is defined along with the requirements of each test.

3.5.5

valve base electronics

electronic unit, at earth potential, which is the interface between the converter control system and the VSC valves

4 General requirements

4.1 Guidelines for the performance of type tests

4.1.1 Evidence in lieu

Each design of valve shall be subjected to the type tests specified in this standard. If the valve is demonstrably similar to one previously tested, the supplier may, in lieu of performing a type test, submit a test report of a previous type test for consideration by the purchaser. This should be accompanied by a separate report detailing the differences in the design and demonstrating how the referenced type test satisfies the test objectives for the proposed design.

4.1.2 Test object

This subclause does not apply to tests on the valve supporting structure and multiple valve unit. The test object for those tests is defined in 7.2 and 8.2.

a) Type tests may be performed either on a complete valve or, in certain circumstances, on valve sections, as indicated in Table 3.

b) The minimum number of valve levels to be tested, depending on the valve levels in a single valve, is as shown in Table 1.

Table 1 – Minimum number of valve levels to be tested as a function of the number of valve levels per valve

Number of valve levels per valve	Total number of valve levels to be tested
1 – 50	Number of valve levels in one valve
51 – 250	50
≥ 251	20 %

c) Generally, the same valve sections are recommended to be used for all type tests. However, with the agreement of the purchaser and supplier, different tests may be performed on different valve sections in parallel, in order to speed up the programme for executing the tests.

d) Prior to commencement of type tests, the valve, valve sections and/or the components of them should be demonstrated to have withstood the production tests to ensure proper manufacture.

4.1.3 Sequence of test

In order to confirm that the valve terminal-terminal insulation has not been degraded by the fast repetitive switching stresses experienced by the converter in operation, the valve a.c. – d.c. voltage test between terminals with partial discharge measurement should be performed after the operational tests. Other type tests specified can be carried out in any order.

NOTE For valves of the "controllable voltage source" type (Clause A.5), the test sequence, where the a.c. – d.c. voltage test is performed before the operational test, may be acceptable by mutual agreement between the purchaser and supplier.

4.1.4 Test procedure

The tests shall be performed in accordance with IEC 60060, where applicable.

4.1.5 Ambient temperature for testing

The tests shall be performed in accordance with IEC 60060, where applicable.

4.1.6 Frequency for testing

AC dielectric tests can be performed at either 50 Hz or 60 Hz. For operational tests, specific requirements regarding the frequency for testing are given in the relevant clauses.

4.1.7 Test reports

At the completion of the type tests, the supplier shall provide type test reports in accordance with Clause 14.

4.2 Atmospheric correction factor

When specified in the relevant clause, atmospheric correction shall be applied to the test voltages in accordance with IEC 60060-1. The reference conditions to which correction shall be made are the following:

– pressure:

  - If the insulation coordination of the tested part of the valve is based on standard rated withstand voltages according to IEC 60071-1, correction factors are only applied for altitudes exceeding 1 000 m. Hence if the altitude of the site a_s at which the equipment will be installed is ≤1 000 m, then the standard atmospheric air pressure (b_0= 101,3 kPa) shall be used with no correction for altitude. If a_s >1 000 m, then the standard procedure according to IEC 60060-1 is used except that the reference atmospheric pressure b_0 is replaced by the atmospheric pressure corresponding to an altitude of 1 000 m ($b_{1000\text{m}}$).

- If the insulation coordination of the tested part of the valve is not based on standard rated withstand voltages according to IEC 60071-1, then the standard procedure according to IEC 60060-1 is used with the reference atmospheric pressure b_0 (b_0=101,3 kPa).

– temperature: design maximum valve hall air temperature (°C);

– humidity: design minimum valve hall absolute humidity (g/m^3).

The values to be used shall be specified by the supplier.

4.3 Treatment of redundancy

4.3.1 Operational tests

For operational tests, redundant valve levels shall not be short-circuited. The test voltages used shall be adjusted by means of a scaling factor k_n:

$$k_\text{n} = \frac{N_\text{tut}}{N_\text{t} - N_\text{r}}$$

where

N_tut is the number of series valve levels in the test object;

N_t is the total number of series valve levels in the valve;

N_r is the total number of redundant series valve levels in the valve.

4.3.2 Dielectric tests

For all dielectric tests between valve terminals, the redundant valve levels shall be short-circuited. The location of valve levels to be short-circuited shall be agreed by the purchaser and supplier.

NOTE Depending on the design, limitations may be imposed upon the distribution of short-circuited valve levels. For example, there may be an upper limit to the number of short-circuited valve levels in one valve section.

For all dielectric tests on valve section, the test voltages used shall be adjusted by means of a scaling factor k_o:

$$k_\text{o} = \frac{N_\text{tu}}{N_\text{t} - N_\text{r}}$$

where

N_tu is the number of series valve levels not short circuit connected in the test object;

N_t is the total number of series valve levels in the valve;

N_r is the total number of redundant series valve levels in the valve.

4.4 Criteria for successful type testing

4.4.1 General

Experience in semiconductor application shows that, even with the most careful design of valves, it is not possible to avoid occasional random failures of valve level components during service operation. Even though these failures may be stress-related, they are considered random to the extent that the cause of failure or the relationship between failure rate and stress cannot be predicted or is not amenable to precise quantitative definition. Type tests subject valves or valve sections, within a short time, to multiple stresses that generally correspond to the worst stresses that can be experienced by the equipment not more than a few times during the life of the valve. Considering the above, the criteria for successful type testing set out below therefore permit a small number of valve levels to fail during type testing, providing that the failures are rare and do not show any pattern that is indicative of inadequate design.

4.4.2 Criteria applicable to valve levels

Criteria applicable to valve levels are as follows.

a) If, following a type test as listed in Clause 5, more than one valve level (alternatively more than 1 % of the tested valve levels, if greater) has become short-circuited, then the valve shall be deemed to have failed the type tests.

b) If, following a type test, one valve level (or more if still within the 1 % limit) has become short-circuited, then the failed level(s) shall be restored and this type test repeated.

c) If the cumulative number of short-circuited valve levels during all type tests is more than 3 % of the tested valve levels, then the valve shall be deemed to have failed the type test.

d) The valve or valve sections shall be checked after each type test to determine whether or not any valve levels have become short-circuited. Failed IGBT/diode or auxiliary components found during or at the end of a type test may be replaced before further testing.

e) At the completion of the test programme, the valve or valve sections shall undergo a series of check tests, which shall include as a minimum:
   - check for voltage withstand of valve levels;
   - check of the gating circuits;
   - check of the monitoring circuits;
   - check of any protection circuits forming an integral part of the valve;
   - check of the voltage grading circuits.

f) Valve levels short circuits occurring during the check tests shall be counted as part of the criteria for acceptance defined above. In addition to short-circuited levels, the total number of valve levels exhibiting faults which do not result in valve level short circuit, which are discovered during the type test programme and the subsequent check test, shall not exceed 3 % of the number of tested valve levels in dielectric and operational type tests, whichever is lower. If the total number of such levels exceeds 3 %, then the nature of the faults and their cause shall be reviewed and additional action, if any, agreed between purchaser and supplier.

g) When applying the percentage criteria to determine the permitted maximum number of short-circuited valve levels and the permitted maximum number of levels with faults which have not resulted in a valve level becoming short-circuited, it is usual practice to round off all fractions to the next highest integer, as illustrated in Table 2.

Table 2 – Valve level faults permitted during type tests

Number of valve levels tested	Number of valve levels permitted to become short-circuited in any one type test	Total number of valve levels permitted to become short-circuited in all type tests	Additional number of valve levels, in all type tests, which have experienced a fault but have not become short-circuited
Up to 33	1	1	1
34 to 67	1	2	2
68 to 100	1	3	3
etc.			

The distribution of short-circuited levels and of other valve level faults at the end of all type tests shall be essentially random and not show any pattern that may be indicative of inadequate design.

4.4.3 Criteria applicable to the valve as a whole

Breakdown of or external flashover across common electrical equipment associated with more than one valve level of the valve, or disruptive discharge in dielectric material forming part of the valve structure, cooling ducts, light guides or other insulating parts of the pulse transmission and distribution system shall not be permitted.

Component and conductor surface temperatures, together with associated current-carrying joints and connections, and the temperature of adjacent mounting surfaces shall at all times remain within limits permitted by the design.

5 List of type tests

Table 3 lists the type tests given in Clauses 6 to 12.

Table 3 – List of type tests

Type test	Clause or subclause	Test object
Maximum continuous operating duty test	6.4	Valve or valve section
Maximum temporary over-load operating duty test	6.5	Valve or valve section
Minimum d.c. voltage test	6.6	Valve or valve section
Valve support d.c. voltage test	7.3.1	Valve support
Valve support a.c. voltage test	7.3.2	Valve support
Valve support switching impulse test	7.3.3	Valve support
Valve support lightning impulse test	7.3.4	Valve support
MVU d.c. voltage test to earth	8.3.1	MVU
MVU a.c. voltage test	8.3.2	MVU
MVU switching impulse test	8.3.3	MVU
MVU lightning impulse test	8.3.4	MVU
Valve a.c. – d.c. voltage test	9.3.1	Valve (or valve section if agreed between supplier and purchaser)
Valve switching impulse test	9.3.3	
Valve lightning impulse test	9.3.4	
IGBT overcurrent turn-off test	10	Valve or valve section
Short-circuit current test	11	Valve or valve section
Test for valve insensitivity to electromagnetic disturbance	12	Valve (or valve section if agreed between supplier and purchaser)

6 Operational tests

6.1 Purpose of tests

The principal objectives of the operational tests are:

a) to check the adequacy of the VSC/diode level and associated electrical circuits in a valve with regard to current, voltage and temperature stresses in the conducting state, at turn-on and turn-off under the worst repetitive stress conditions;

b) to demonstrate correct interaction between valve electronics and power circuits of the VSC valves.

6.2 Test object

The tests may be performed on either the complete valve or on valve sections. The choice depends mainly upon the valve design and the test facilities available. The tests specified in this clause are valid for valve sections containing five or more series-connected VSC/diode levels. If tests with fewer than five levels are proposed, additional test safety factors shall be agreed. Under no circumstances shall the number of series-connected levels for tests be less than three.

The valve or valve sections under test shall be assembled with all auxiliary components. When required, a proportionally scaled valve arrester shall be included. The arrester shall be scaled to the number of series-connected levels under test to give a protective level which corresponds at least to the maximum characteristic of the service arrester.

The coolant shall be in a condition representative of service conditions. Flow and temperature, in particular, shall be set to the most unfavourable values appropriate to the test in question, such that the relevant component temperature(s) are equal to the values applicable in service.

6.3 Test circuit

For valve designs which act as a controllable voltage source and contain in-built d.c. capacitance, the d.c. capacitance and its connections to the semiconductor devices are an integral part of the test object.

However, for valve designs which function as switches, where the d.c. capacitor is separate from the valve, the d.c. capacitor needs to be correctly represented in the test circuit. In particular, the series-stray inductance in the connections between the d.c. capacitor and the valve, and the stray capacitance across the valve section, shall be correctly reproduced and scaled to the size of valve section under test. Test circuit interconnections shall be of a type that is representative of the type used in the converter, in order not to introduce unrealistic levels of damping due to skin effects.

6.4 Maximum continuous operating duty test

The test needs to reproduce the following parameters based on the worst in service operating conditions of the converter. More than one test may be necessary to reproduce all parameters at their maximum values.

For VSC valves:

- maximum continuous IGBT junction temperatures;
- maximum continuous FWD junction temperatures;
- maximum continuous snubber component temperatures;
- maximum continuous turn-on and turn-off voltage and current.

For diode valves:

- maximum continuous diode junction temperature;
- maximum continuous snubber component temperatures;
- maximum continuous diode turn-off voltage and current.

All of these parameters need to be reproduced during the maximum continuous operating duty test. They may be reproduced either in separate tests or as a combined test.

The test voltage shall be based on the maximum continuous direct voltage, the test switching frequency shall be based on the maximum continuous switching frequency and the modulation pattern shall be representative of that used in service. The coolant temperature shall be not less than that which will give the highest steady-state IGBT junction and/or Diode junction temperatures in service.

The test current, in r.m.s. value, shall incorporate a test safety factor of 1,05.

The test voltage U_{tpv1} corresponding to the maximum continuous operating d.c. voltage shall be determined as follows:

$$U_{\mathrm{tpv1}} = U_{\mathrm{dmax}} \cdot k_{\mathrm{n}} \cdot k_1$$

where

U_{dmax} is the maximum continuous operating d.c. voltage, including ripple;
k_{n} is a test scaling factor according to 4.3.1;
k_1 is a test safety factor;
k_1 = 1,05.

The duration of the test shall be not less than 30 min after the exit coolant temperature has stabilized.

6.5 Maximum temporary over-load operating duty test

If the valve is specified for temporary over-load operation, a maximum temporary operating duty test shall be performed.

The test conditions, where required, shall be determined using the same methodology as in 6.4 above.

Prior to the test, the valve or valve section shall be brought to thermal equilibrium under the conditions of 6.4. The temporary operating duty test is then started from this initial condition and continued for a duration equal to the duration of the temporary overload multiplied by 1,2.

After the temporary over-load operation duty test, 10 min maximum continuous operating duty test shall be performed.

6.6 Minimum d.c. voltage test

This test is to verify the correct performance of those valve designs in which energy for the valve electronic circuits is extracted from the voltage appearing between the valve terminals.

The test consists of applying a d.c. voltage between the terminals of the valve or valve section. For this test, only the voltage, not the current, is important.

The correct operation of the valve electronic circuits may be demonstrated either by deblocking the valve or valve section, or by remaining in the blocked state and monitoring the databack signals from the valve electronics.

The test voltage U_{min} is defined as:

$$U_{\mathrm{min}} = \frac{N_{\mathrm{tut}}}{N_{\mathrm{t}}} \cdot U_{\mathrm{W}} \cdot k_2$$

where

U_W is the lowest d.c. voltage across one valve in service operation where proper function of the valve electronics is require;

N_{tut} is the number of series-connected VSC levels under test;

N_t is the total number of series-connected VSC levels in a single valve, including redundancy;

k_2 is a test safety factor;

k_2 = 0,95.

The duration of test shall be not less than 10 min.

7 Dielectric tests on valve support structure

7.1 Purpose of tests

The principal objectives of these tests are:

a) to verify the voltage withstand capability of the insulation of the valve support, cooling ducts, light guides and other insulating components associated with the valve support. If there is insulation to earth other than the valve support, then additional tests may be necessary;

b) to verify that the partial discharge inception and extinction voltages are above the maximum operating voltage appearing on the valve support.

NOTE Depending upon the application, it may be possible to eliminate some of the tests on the valve support, subject to agreement between purchaser and supplier.

7.2 Test object

The valve support to be used for the tests may be a representative separate object including representation of the adjacent parts of the valve, or may form part of the assembly used for single valve or multiple valve unit tests. It shall be assembled with all ancillary components in place and shall have the adjacent earth potential surfaces properly represented. The coolant shall be in a condition representative of the most onerous service condition for the purpose of the test.

If a single valve consists of more than one structure such that there is more than one valve support structure per valve, then it shall be demonstrated that the tests proposed cover the worst stresses experienced by any of the valve support structures.

7.3 Test requirements

All test levels below are subject to atmospheric correction as described in 4.2.

7.3.1 Valve support d.c. voltage test

The two main terminals of the valve shall be connected together and the d.c. voltage then applied between the two main terminals thus connected and earth. Starting from a voltage not higher than 50 % of the maximum test voltage, the voltage shall be raised to the specified 1 min test voltage in approximately 10 s, kept constant for 1 min, reduced to the specified 3 h test voltage, kept constant for 3 h and then reduced to zero. During the last hour of the specified 3 h test, the number of partial discharges exceeding 300 pC shall be recorded as described in Annex B of IEC 60700-1.

The number of pulses exceeding 300 pC shall not exceed 15 pulses per minute, averaged over the recording period. Of these, no more than seven pulses per minute shall exceed 500 pC, no more than three pulses per minute shall exceed 1 000 pC and no more than one pulse per minute shall exceed 2 000 pC.

NOTE If an increasing trend in the magnitude or rate of partial discharge is observed, the test duration may be extended by mutual agreement between the purchaser and supplier.

The test shall then be repeated with the voltage of opposite polarity.

Prior to the test, the valve support shall be short-circuited and earthed for a minimum of 2 h.

The valve support d.c. test voltage U_{tds} shall be determined in accordance with the following:

$$U_{\text{tds}} = \pm U_{\text{dmS}} \cdot k_3 \cdot k_t$$

where

U_{dmS} is the maximum value of the d.c. component of the steady-state operating voltage appearing across the valve support;

k_3 is a test safety factor;

k_3 = 1,6 for the 1 min test;

k_3 = 1,1 for the 3 h test;

k_t is the atmospheric correction factor;

k_t is the value according to 4.2 for the 1 min test;

k_t =1,0 for the 3 h test.

7.3.2 Valve support a.c. voltage test

To perform the test, the two main terminals of the valve shall be connected together, and the a.c. test voltage then applied between the two main terminals thus connected and earth. Starting from a voltage not higher than 50 % of the maximum test voltage, the voltage shall be raised to the specified 1 min test voltage U_{tas1} within approximately 10 s, kept constant for 1 min, reduced to the specified 30 min test voltage U_{tas2}, kept constant for 30 min and then reduced to zero. During the last 1 min of specified 30 min test, the level of partial discharge shall be monitored and recorded. If the value of partial discharge is below 200 pC, the design may be accepted unconditionally. If the value of partial discharge exceeds 200 pC, the test results shall be evaluated.

The r.m.s. value of the valve support a.c. test voltage U_{tas} shall be determined in accordance with the following:

$$U_{\text{tas}} = \frac{U_{\text{mS}}}{\sqrt{2}} \cdot k_r \cdot k_4 \cdot k_t$$

where

U_{mS} is the peak value of the maximum repetitive operating voltage across the valve support during steady-state operation, including switching overshoot;

U_{tas1} is the 1 min test voltage;

U_{tas2} is the 30 min test voltage;

k_4 is a test safety factor;

k_4 = 1,3 for the 1 min test;

k_4 = 1,15 for the 30 min test;

k_t is the atmospheric correction factor;

k_t is the value according to 4.2 for the 1 min test;

k_t = 1,0 for the 30 min test;

k_r is the temporary overvoltage factor;

k_r is the value determined from system studies for the 1 min test;

k_r = 1,0 for the 30 min test.

7.3.3 Valve support switching impulse test

The test shall comprise three applications of positive polarity and three applications of negative polarity switching impulse voltages between the main terminals of the valve (connected together) and earth.

A standard switching impulse voltage wave shape in accordance with IEC 60060 shall be used.

The test voltage shall be selected in accordance with the insulation co-ordination of the VSC substation.

7.3.4 Valve support lightning impulse test

The test shall comprise three applications of positive polarity and three applications of negative polarity lightning impulse voltages between the main terminals of the valve (connected together) and earth.

A standard lightning impulse voltage wave shape in accordance with IEC 60060 shall be used.

The test voltage shall be selected in accordance with the insulation co-ordination of the VSC substation.

8 Dielectric tests on multiple valve unit

This clause is only applicable if more than one valve is installed in a common valve structure (multiple valve unit). In the case where each individual valve is mounted in a dedicated valve structure, this clause is not applicable.

8.1 Purpose of tests

The principal objectives of these tests are:

a) to verify the voltage withstand capability of the external insulation of the MVU, with respect to its surroundings, especially for the valve(s) connected at pole potential;
b) to verify the voltage withstand capability between single valves in a MVU structure;
c) to verify that the partial discharge levels are within specified limits.

8.2 Test object

There are many possible arrangements of valves and multiple valve units. The test object(s) shall be chosen to reflect, as accurately as possible, the service configuration of valves insofar as is necessary for the test in question. The test object shall be fully equipped unless it can be shown that some components can be simulated or omitted without reducing the significance of the results.

Individual valves may have to be short-circuited depending on the configuration of the MVU and the objectives of the test.

When the low-voltage terminal of the MVU is not connected to earth potential, care shall be taken to suitably terminate the low voltage terminal of the MVU during tests to correctly simulate the voltage appearing at this terminal. Earth planes shall be used, whose separation shall be determined by the proximity of other valves and earth potential surfaces.

8.3 Test requirements

8.3.1 MVU d.c. voltage test to earth

The d.c. test voltage shall be applied between the highest potential d.c. terminal of the MVU and earth.

Starting from a voltage not higher than 50 % of the maximum test voltage, the voltage shall be raised to the specified 1 min test voltage in approximately 10 s, kept constant for 1 min, reduced to the specified 3 h test voltage, kept constant for 3 h and then reduced to zero.

During the last hour of the specified 3 h test, the number of partial discharges exceeding 300 pC shall be recorded.

The number of pulses exceeding 300 pC shall not exceed 15 pulses per minute, averaged over the recording period. Of these, no more than seven pulses per minute shall exceed 500 pC, no more than three pulses per minute shall exceed 1 000 pC, and no more than one pulse per minute shall exceed 2 000 pC.

NOTE If an increasing trend in the magnitude or rate of partial discharge is observed, the test duration may be extended by mutual agreement between the purchaser and supplier.

The test shall then be repeated with the voltage of opposite polarity.

Prior to the test, the MVU terminals shall be short-circuited together and earthed for a minimum of 2 h.

The MVU d.c. test voltage U_{tdm} shall be determined in accordance with the following:

$$U_{\mathrm{tdm}} = \pm U_{\mathrm{dmm}} \cdot k_5 \cdot k_{\mathrm{t}}$$

where

U_{dmm} is the maximum value of the d.c. component of the steady-state operating voltage appearing between the high-voltage terminal of the MVU and earth;

k_5 is a test safety factor;

k_5 = 1,6 for the 1 min test;

k_5 = 1,1 for the 3 h test;

k_{t} is the atmospheric correction factor;

k_{t} is the value according to 4.2 for the 1 min test;

k_{t} = 1,0 for the 3 h test.

8.3.2 MVU a.c. voltage test

If a MVU experiences a.c. or composite a.c. plus d.c. voltage stresses between any two terminals, the withstand capability of which is not adequately demonstrated by other tests, then it will be necessary to perform an a.c. voltage test between these terminals of the MVU.

To perform the test, the test voltage source shall be connected to the pair of MVU terminals in question. The point of earth connection is dependent on the test circuit arrangement.

Starting from a voltage not higher than 50 % of the 1 min test voltage, the voltage shall be raised to the specified 1 min test voltage, kept constant for 1 min, then reduced to the 30 min value, kept constant for 30 min and then reduced to zero.

During the specified 30 min test, the level of partial discharge shall be monitored and recorded. If the value of partial discharge is below 200 pC, the design may be accepted unconditionally. If the value of partial discharge exceeds 200 pC, the test results shall be evaluated.

The r.m.s. value of the MVU a.c. test voltage U_{tam} shall be determined in accordance with the following:

$$U_{\mathrm{tam}} = \frac{U_{\mathrm{mm}}}{\sqrt{2}} \cdot k_{\mathrm{r}} \cdot k_6 \cdot k_{\mathrm{t}}$$

where

U_{mm} is the peak value of the maximum repetitive operating voltage appearing between the terminals of the MVU during steady-state operation, including switching overshoot;

k_6 is a test safety factor;

k_6 = 1,3 for the 1 min test;

k_6 = 1,15 for the 30 min test;

k_{r} is the temporary overvoltage factor;

k_{r} is the value determined from system studies for the 1 min test;

k_{r} = 1,0 for the 30 min test;

k_{t} is the atmospheric correction factor;

k_{t} is the value according to 4.2 for the 1 min test;

k_{t} = 1,0 for the 30 min test.

8.3.3 MVU switching impulse test

A standard switching impulse voltage waveshape in accordance with IEC 60060 shall be used.

The MVU switching impulse test voltage shall be applied between the high voltage terminal of the MVU and earth.

The test shall comprise three applications of positive polarity and three applications of negative polarity switching impulse voltage of a specified amplitude.

The MVU switching impulse test voltage U_{tsm} shall be determined in accordance with the following:

$$U_{\mathrm{tsm}} = \pm SIPL_{\mathrm{m}} \cdot k_7 \cdot k_{\mathrm{t}}$$

where

$SIPL_{\mathrm{m}}$ is the switching impulse protective level determined by insulation co-ordination taking into account the arrester(s) connected between the MVU high voltage terminal and earth;

k_7 is a test safety factor;

k_7 = 1,10;

k_{t} is the atmospheric correction factor;

k_{t} is the value according to 4.2.

If the test prescribed above does not adequately test the switching impulse withstand between all terminals of the MVU, then consideration shall be given to performing extra tests to check the insulation.

NOTE Subject to agreement between the purchaser and supplier, the MVU switching impulse test need not be performed if it can be shown by other means that:

a) the external air clearances to other valves and to earth are adequate for the switching impulse voltage withstand level required, and

b) the switching impulse withstand between any two terminals of the MVU is adequately demonstrated by other tests.

8.3.4 MVU lightning impulse test

A standard lightning impulse voltage wave shape in accordance with IEC 60060 shall be used.

The MVU lightning impulse test voltage shall be applied between the high voltage terminal of the MVU and earth.

The test shall comprise three applications of positive polarity and three applications of negative polarity lightning impulse voltage of specified amplitude.

The MVU lightning impulse test voltage U_{tlm} shall be determined in accordance with the following:

$$U_{\text{tlm}} = \pm LIPL_{\text{m}} \cdot k_8 \cdot k_{\text{t}}$$

where

$LIPL_{\text{m}}$ is the lightning impulse protective level determined by insulation co-ordination, taking into account the arrester(s) connected between the MVU high voltage terminal and earth;

k_8 is a test safety factor;

k_8 = 1,10;

k_{t} is the atmospheric correction factor;

k_{t} is the value according to 4.2.

If it cannot be demonstrated that the test prescribed above adequately tests the lightning impulse withstand voltage between all terminals of the MVU, then consideration shall be given to performing extra tests to check this insulation.

NOTE Subject to agreement between the purchaser and supplier, the MVU lightning impulse test need not be performed if it can be shown by other means that:

a) the external air clearances to other valves and to earth are adequate for the lightning impulse voltage withstand level required, and

b) the lightning impulse withstand voltage between any two terminals of the MVU is adequately demonstrated by other tests.

9 Dielectric tests between valve terminals

9.1 Purpose of the test

These tests are intended to verify the design of the valve regarding its voltage-related characteristics for various types of overvoltages (d.c., a.c., switching impulse and lightning impulse overvoltages). The tests should demonstrate that:

a) the valve will withstand the specified overvoltages;

b) partial discharges will be within specified limits under specified test conditions;

c) the internal voltage grading circuits have sufficient power rating;

d) the valve electronic circuits behave as expected.

It should be noted that the tests described in this clause are based on standard wave shapes and standard test procedures as developed for the testing of high-voltage a.c. systems and components. This approach offers great advantages to the industry because it allows much of the existing technology of high-voltage testing to be carried over to the qualification of HVDC valves. On the other hand, it must be recognized that a particular HVDC application may result in wave shapes different from the standards and, in this case, the test may be modified so as to realistically reflect expected conditions.

9.2 Test object

The test object should generally be a complete valve. Tests on individual valve sections are acceptable if the supplier can demonstrate that the voltage distribution between valve sections, under test conditions, is representative of the voltage distribution within a complete valve in service. The test valve or valve section shall be assembled with all auxiliary components except for the valve surge arrester. The valve may form part of a multiple valve unit.

For all impulse tests, the valve electronics shall be energized unless otherwise specified.

If valve section is used as test object, the minimum number of valve levels in the test section should be agreed by the purchaser. In such cases, additional tests to verify the insulation between different parts of the complete valve may be needed and shall be agreed between purchaser and supplier.

The coolant shall be in a condition that represents service conditions except for flow rate which can be reduced. If any object external to the structure is necessary for proper representation of the stresses during tests, it shall be included or simulated in the test. Earth planes shall be used, whose separation shall be determined by the proximity of other adjacent valves and earth potential surfaces.

The test object used for the valve dielectric tests will normally not permit the application of atmospheric correction to the specified test voltages without overstressing the internal components. For this reason, no atmospheric correction factor is applied to any of the dielectric tests between valve terminals. The supplier shall demonstrate that the effects of atmospheric conditions on the valve internal withstand have been allowed for adequately.

9.3 Test requirements

9.3.1 Valve a.c. – d.c. voltage test

This test consists of a short-duration test and a long-duration test. The short-duration test reproduces the composite a.c. – d.c. voltage resulting from certain converter or system faults.

The worst case will depend upon the valve design. The cases to be considered include, but are not limited to, the following:

- a.c. terminal short circuit to ground;
- a.c. terminal short circuit between phases;
- a.c. terminal open circuit;
- a.c. system load-rejection;
- short circuit across or misfiring of another valve in the same phase unit;
- d.c. pole earth fault to ground.

In this test, a capacitor can be used in conjunction with an a.c. test voltage source to produce a composite a.c. – d.c. voltage waveform. Depending on the converter topology, the capacitor could be an integral part of the valve, or it could be a separate item (part of the test circuit, not part of the test object).

Alternatively, a separate d.c. voltage source could be used to substitute the capacitor.

Starting from a voltage not higher than 50 % of the maximum test voltage, the voltage shall be ramped up to the specified 10 s test level within approximately 10 s, reduced to the specified 30 min test voltage, kept constant for 30 min and then reduced to zero.

The peak value of the periodic partial discharge recorded during the last minute of 30 min test shall be less than 200 pC, provided that the components which are sensitive to partial discharge in the valve have been separately tested. The number of pulses exceeding 300 pC shall not exceed 15 per minute, averaged over the record period. Of these, no more than seven pulses per minute shall exceed 500 pC, no more than three pulses per minute shall exceed 1 000 pC and no more than one pulse per minute shall exceed 2 000 pC.

NOTE 1 If an increasing trend in the rate or magnitude of partial discharge is observed, the test duration may be extended by mutual agreement between the purchaser and supplier.

NOTE 2 It may be necessary to disable gate units or other auxiliary circuits in this test in order to prevent interference with partial discharge measurement, for example, from gate unit power supply circuits.

The valve test voltages have a sinusoidal waveshape superimposed on a d.c. level.

The valve 10 s test voltage U_{tv1} shall be determined in accordance with the following:

$$U_{tv1} = \left(U_{ac1} \cdot \sin(2\pi ft) + U_{dc1}\right) \cdot k_o \cdot k_9$$

where

U_{ac1} is the peak value of maximum transient a.c. component over-voltage across valve. The limiting effect of valve arrester or pole arrester can be taken into account to derive the over-voltage in service condition;

U_{dc1} is the maximum transient d.c. component over-voltage across valve. The limiting effect of valve arrester or pole arrester can be taken into account to derive the over-voltage in service condition;

k_o is a test scaling factor according to 4.3.2;

k_9 is a test safety factor;

k_9 = 1,10;

f is the test frequency (50 Hz or 60 Hz depending on test facilities).

The valve 30 min test voltage U_{tv2} shall be determined in accordance with the following:

$$U_{tv2} = U_{tac2} + U_{tdc2}$$

$$U_{tac2} = \frac{\sqrt{2} \cdot U_{max-cont} \cdot \sin(2\pi ft)}{\sqrt{3}} \cdot k_o \cdot k_{10}$$

$$U_{tdc2} = U_{dmax} \cdot k_o \cdot k_{10}$$

$U_{max\text{-}cont}$ is the maximum steady-state phase-to-phase voltage on the a.c. system or the valve side of the transformer, if a converter transformer is used in between a.c. system and converters;

U_{dmax} is the maximum value of the d.c. component of the steady-state operating voltage of the d.c. system;

k_o is a test scaling factor according to 4.3.2;

k_{10} is a test safety factor;

k_{10} = 1,10;

f is the test frequency (50 Hz or 60 Hz depending on test facilities).

NOTE 3 The use of a capacitor instead of a d.c. source in the test circuit should be mutually agreed by manufacturer and purchaser as the test voltage is higher than actual value.

9.3.2 Valve impulse tests (general)

The following should be taken into account during valve impulse tests.

a) For some applications, for instance no overhead line is present in d.c. side and the busbar between phase reactor and valves is completely protected against direct lightning strike in a.c. side or in topologies, where the valve acts as a controllable voltage source with its own inbuilt d.c. capacitance, the valve impulse tests are less important since the valves don't see impulses at an amplitude which could be decisive in the electric performance of valves. Impulse tests in such applications can be omitted.
b) The impulse test will be applied only in one polarity which corresponds to the polarity of valve withstand voltage.
c) If the valve impulse withstand levels are equal to or less than the valve a.c. – d.c. test level, it is deemed that the valve a.c. – d.c. test can cover the impulse tests.

9.3.3 Valve switching impulse test

A standard switching impulse voltage waveshape in accordance with IEC 60060 shall be used.

The test shall comprise three applications of switching impulse voltages of specified amplitude on the valve.

The valve switching impulse test withstand voltage U_{tsv} shall be determined in accordance with the following.

– Valve with valve arrester protection:

$$U_{\mathrm{tsv}} = SIPL_{\mathrm{v}} \cdot k_{\mathrm{o}} \cdot k_{11}$$

where

$SIPL_{\mathrm{v}}$ is the switching impulse protective level of the valve arrester;

k_{o} is a test scaling factor according to 4.3.2;

k_{11} is a test safety factor;

k_{11} = 1,10.

– Valve without valve arrester protection:

This test is intended to verify the valve insulation when the valve is not directly protected by surge arresters.

$$U_{\mathrm{tsv}} = U_{\mathrm{cms}} \cdot k_{\mathrm{o}} \cdot k_{12}$$

where

U_{cms} is the switching impulse prospective voltage across valve terminals according to system insulation coordination studies;

k_{o} is a test scaling factor according to 4.3.2;

k_{12} is a test safety factor;

k_{12} = 1,3.

The valve shall withstand the test voltage without switching or insulation breakdown.

9.3.4 Valve lightning impulse test

A standard lightning impulse voltage waveshape in accordance with IEC 60060 shall be used.

The test shall comprise three applications of impulse voltages of specified amplitude on the valve.

The valve lightning impulse withstand voltage U_{tlv} shall be determined in accordance with the following.

– Valve with valve surge arrester protection:

$$U_{\text{tlv}} = LIPL_{\text{v}} \cdot k_{\text{o}} \cdot k_{13}$$

where

$LIPL_{\text{V}}$ is the lightning impulse protective level of the valve arrester;

k_{o} is a test scaling factor according to 4.3.2;

k_{13} is a test safety factor;

k_{13} = 1,10.

– Valve without valve surge arrester protection:

This test is intended to verify the valve insulation when the valve is not directly protected by surge arresters.

$$U_{\text{tlv}} = U_{\text{cml}} \cdot k_{\text{o}} \cdot k_{14}$$

where

U_{cml} is the lightning impulse prospective voltage across valve terminals according to system insulation coordination studies;

k_{o} is a test scaling factor according to 4.3.2;

k_{14} is a test safety factor;

k_{14} = 1,3.

The valve shall withstand the test voltage without switching or insulation breakdown.

10 IGBT overcurrent turn-off test

10.1 Purpose of test

The principal objective is to check the adequacy of the VSC valve design, especially the IGBT, and the associated electrical circuits with regard to current and voltage stresses at turn-off in the event of certain short circuit faults or misfiring events.

The test shall replicate the worst combination of voltage stress and instantaneous junction temperature, based on conditions that represent the most unfavourable tolerance settings of the monitoring/protection circuits.

General requirements related to the test circuit and the representation of d.c. capacitor, loop stray inductance, etc. are as stated in 6.3.

The worst case will depend upon the valve design but the cases to be considered include, but are not limited to, the following:

- a.c. terminal short circuit to ground;
- a.c. terminal short circuit between phases;
- short circuit across or misfiring of another valve in the same phase unit.

10.2 Test object

As described in 6.2. However, it shall also be necessary to represent certain protection or monitoring circuits if these are essential for the detection of an overcurrent event.

10.3 Test requirements

The test consists of operating the test object to thermal equilibrium under the conditions which lead to the highest steady-state junction temperature of the relevant IGBT (see 6.4) and then initiating an overcurrent event. The control and protection system then detects the overcurrent and suppresses the overcurrent by turning off the IGBTs at a current below the maximum safe turn-off limit.

The test voltage U_{tpv2} corresponding to the maximum temporary d.c. over-voltage shall be determined as follows:

$$U_{\text{tpv2}} = U_{\text{dtemp}} \cdot k_{\text{n}} \cdot k_{15}$$

where

U_{dtemp} is the maximum temporary d.c. over-voltage, including ripple;
k_{n} is a test scaling factor according to 4.3.1;
k_{15} is a test safety factor;
k_{15} = 1,05.

The test current waveform in the time interval between detection of the overcurrent and the instant of turn-off of the IGBTs should be representative of the service condition, particularly in terms of current rate-of-rise di/dt.

11 Short-circuit current test

11.1 Purpose of tests

The principal objective is to check the adequacy of the devices, especially the diodes, and the associated electrical circuits with regard to current stresses under specified short circuit conditions, such as short-circuit fault at d.c. side, until the control and protection circuit breaks the fault current. Energization of converter valve should also be considered.

11.2 Test object

As described in 6.2.

11.3 Test requirements

The test consists of operating the test object to thermal equilibrium under the conditions which lead to the highest steady-state junction temperature of the relevant semiconductor component (see 6.4) and then initiating a fault current event.

The fault current amplitude, duration and the number of cycles should be the maximum values expected in the actual field operation. No test safety factor is applied to the current.

Where the test object experiences a recovery voltage between cycles of fault current, then this recovery voltage, including commutation overshoot where applicable, shall also be reproduced during the test. A test safety factor of 1,05 is applied to the recovery voltage.

12 Tests for valve insensitivity to electromagnetic disturbance

12.1 Purpose of tests

The principal objective is to demonstrate the insensitivity of the valve to electromagnetic interference (electromagnetic disturbance) arising from voltage and current transients generated within the valve and imposed on it from the outside. The sensitive elements of the valve are generally electronic circuits used for controlling, protection and monitoring of the valve levels.

Generally, the valve insensitivity to electromagnetic disturbance can be checked by monitoring the valve during other type tests. Of these, the valve and the valve maximum continuous operating duty test and maximum temporary overload operating duty test (see 6.4 and 6.5), the valve impulse test (see 9.3.3 and 9.3.4) and the IGBT overcurrent turn-off test (see Clause 10) are the most important.

The tests shall demonstrate that:

a) out-of-sequence or spurious switching of IGBT does not occur;
b) the electronic protection circuits installed in the valve operate as intended;
c) false indication of valve level faults or erroneous signals sent to the converter control and protection systems by the valve base electronics, arising from receipt of false data from the valve monitoring circuits, does not occur.

NOTE For this standard, tests to demonstrate valve insensitivity to electromagnetic disturbance apply only to the VSC valve and that part of the signal transmission system that connects the valve to earth. Demonstration of the insensitivity to electromagnetic disturbance of equipment located at earth potential and characterization of the valve as a source of electromagnetic disturbance for other equipment are not within the scope of this standard.

12.2 Test object

Generally, the test object is the valve or valve sections as used for other tests.

When insensitivity to electromagnetic disturbance arising from coupling between adjacent valves in a MVU is to be demonstrated, two approaches are acceptable as defined in 12.3. In this case, the test object will be a separate valve or valve section according to the approach adopted.

12.3 Test requirements

12.3.1 General

When demonstrating insensitivity to electromagnetic disturbance arising from coupling between adjacent valves of a MVU, the test requirements depend on which of the two recommended approaches is adopted.

NOTE The specific geometric arrangement to be used and the magnitude of the forward voltage for the electromagnetic disturbance test object should be agreed, based on the design of MVU.

12.3.2 Approach one

Approach one is to simulate the source of electromagnetic disturbance directly as part of a test set-up. Such a test set-up will require more than one valve or valve section in order to check for interaction between them. The geometric arrangements of the source of the electromagnetic disturbance with respect to the valve under test shall be as close as possible to the service arrangement (or worse from an electromagnetic disturbance point of view). The electronics of the electromagnetic disturbance test object shall be energized. Those parts of the valve base electronics that are necessary for the proper exchange of information with the electromagnetic disturbance test object shall be included.

12.3.3 Approach two

Approach two is to determine the intensity of electromagnetic fields under worst operational conditions, either from theoretical considerations or by measurements. In a second step, these fields are simulated by a test circuit which generates correct (or worse) electromagnetic radiation at the respective frequencies. A valve section is then exposed to the fields generated by the test source.

An essential prerequisite to approach two is the determination of the dynamic field strength and direction at key locations in the valve. This can generally be obtained from search coil measurements taken during firing tests on a single valve. Alternatively, the field can be predicted from three-dimensional field modelling programs. A valve section shall then be tested using a separate field coil to produce field intensity, frequency content and direction which is at least as severe as the predicted values.

The following conditions for the valve section under test shall be met:

- the valve section shall have operational voltage (proportionally scaled) between its terminals and be forward biased at the time of energization of the field coil;
- the electronics of the valve section under test shall be energized;
- those parts of the valve base electronics that are necessary for the proper exchange of information with the valve section shall be included.

12.3.4 Acceptance criteria

The criteria for acceptance for both approaches one and two shall be as defined in 12.1.

13 Production tests

This clause covers tests on assemblies of components that are parts of valves, valve sections, or auxiliary circuits for their protection, control and monitoring. It does not cover tests on individual components that are used within the valve, the valve support, or valve structure.

13.1 Purpose of tests

The purpose of the production tests is to verify proper manufacture by demonstrating that:

- all components and subassemblies used in the valve have been correctly installed in accordance with the design;
- the valve equipment functions as intended and predefined parameters are within prescribed acceptance limits;
- the valve sections and IGBT-diode pair levels (as appropriate) have adequate voltage withstand capability;
- consistency and uniformity in production is achieved.

13.2 Test object

All valve sections or parts thereof manufactured for the project shall be subjected to the routine production tests. The tests may be performed on valve sections or individual levels as appropriate to the design and available test facilities.

13.3 Test requirements

Uniformity in the specified production tests of different suppliers is unnecessary. The production tests shall take into account the special design characteristics of the valve and its components, the extent to which the components are tested prior to assembly, and the particular manufacturing procedures and techniques are involved. In this clause, only production test objectives are given.

In all cases, the supplier shall submit, for approval by the purchaser, a detailed description of the test procedures proposed to meet the production test objectives.

The minimum requirements for routine production tests are listed in 13.4. The order in which the tests are listed implies neither ranking of importance nor the order in which the tests should be performed.

NOTE In some cases, it may be necessary to perform production sample tests on complete assemblies in addition to the routine tests, for example when modifications are introduced in the course of production. The nature and extent of such additional tests should be agreed on a case-by-case basis.

13.4 Production test objectives

13.4.1 Visual inspection

To check that all materials and components are undamaged and are correctly installed in accordance with the latest approved revision of the production documentation.

13.4.2 Connection check

To check that all the main current-carrying connections have been made correctly.

13.4.3 Voltage-grading circuit check

To check the grading circuit parameters and thereby ensure that voltage division between series-connected levels will be correct for applied voltages from d.c. to impulse waveshapes, if applicable.

13.4.4 Control, protection and monitoring circuit checks

To check the function of any control, protection or monitoring circuits that form an integral part of the valve, such as IGBT gate drive circuits and any local protection or monitoring circuits.

If type tests and tests of the effectiveness of fuse protection are considered to be necessary, they shall be specified separately with conditions for tests.

13.4.5 Voltage withstand check

To check that the valve components can withstand the voltage corresponding to the maximum value specified for the valve. The checks shall include a.c. – d.c. test voltage and switching impulse as applicable.

13.4.6 Partial discharge tests

To demonstrate correct manufacture, the purchaser and supplier shall agree which components and subassemblies are critical to the design, and appropriate partial discharge tests shall be performed.

13.4.7 Turn-on / turn-off check

To check that the IGBT(s) in each valve level turns on and turn off correctly in response to switching commands.

13.4.8 Pressure test

To check that there are no coolant leaks.

14 Presentation of type test results

The test report shall be issued in accordance with the general guidelines as given in ISO/IEC 17025, and shall include the following information:

- name and address of the laboratory and location where the tests were carried out;
- name and address of the purchaser;
- unambiguous identification of the test object, including type and ratings, serial number and any other information aimed to identify the test object;
- dates of performance of the tests;
- description of test circuits and test procedures used for the performance of the tests;
- reference to the normative documents and clear description of deviations, if any, from procedures stated in the normative documents;
- description of measuring equipment and statement of the measuring uncertainty;
- test results in the form of tables, graphs, oscillograms, and photographs as appropriate;
- description of equipment or component failure.

Annex A
(informative)

Overview of VSC topology

A.1 General

Voltage sourced converter (VSC) valves are an emerging technology, in which different manufacturers may have substantially different technological approaches and where, in the future, there may be new circuit topologies that have not yet been described.

Voltage sourced converters for HVDC differ fundamentally from conventional HVDC converters (which are current-sourced converters) in that in order to reverse the direction of power flow, it is the direction of direct current, not the polarity of direct voltage, that is reversed. Smoothing of the direct voltage is performed by a large d.c. capacitor, which plays an analogous role to the d.c. inductor (which may partly be fulfilled by the inductance of the d.c. transmission system and the leakage inductance of the converter transformers) in a conventional HVDC project.

In fact, in a great many respects, the role of voltage in a VSC valve is equivalent to that of current in a conventional HVDC thyristor valve, and vice-versa.

A detailed treatment of all possible VSC valve technologies is far beyond the scope of this standard. The purpose of this annex is simply to present a brief overview of the main differences between VSC and conventional HVDC thyristor valves, and of the main types of VSC valve, insofar as they affect the criteria for testing such valves.

This annex is intended to give an overview of the main converter technologies known at the time of writing. However, it is not intended to limit or constrain in any way the types of technology that can be utilized.

A.2 VSC basics

All voltage sourced converters aim to synthesize, from the d.c. capacitor voltage, an approximately sinusoidal voltage at the a.c. terminals. However, in practice, the output voltage of the VSC cannot be perfectly sinusoidal but instead consists of a number of discrete steps of voltage, or “output levels”. The term “level” here refers to a discrete output voltage level and should not be confused with the term “VSC valve level” which refers to an individual IGBT and associated components.

For power systems, 3-phase converters are almost always used, but in considering the number of output levels of a converter, each “phase unit” of the converter is normally considered independently. The number of output levels refers to the number of discrete states in which the line-to-neutral output voltage of a phase unit can exist (Figure A.1). It is important to note that an n-level converter will have ($2n$-1) possible values of line-to-line voltage.

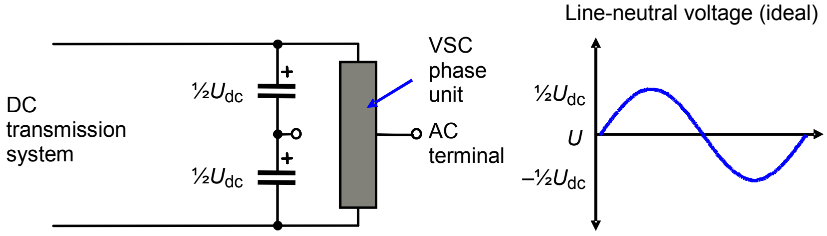

Figure A.1 – A single VSC phase unit and its idealized output voltage

In the simplest possible VSC topology, the "two-level converter", the a.c. output voltage of each phase arm (with respect to the midpoint of the d.c. capacitor, which is normally earthed) has only two possible states: $+½U_{dc}$ and $–½U_{dc}$.

If the VSC valves in this phase arm are switched only at fundamental frequency, the resulting a.c. output voltage waveform is an extremely poor approximation to sinusoidal. Such a waveform would be totally unacceptable in a power system.

However, by switching the valves ON and OFF more than once per fundamental frequency cycle and employing pulse width modulation (PWM) it is possible to obtain an output voltage that is, after filtering, reasonably sinusoidal. Figure A.2 illustrates both cases.

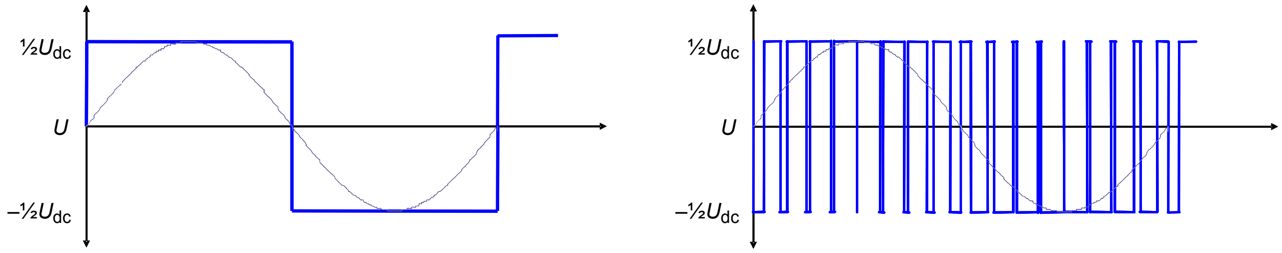

Figure A.2a – Without PWM **Figure A.2b – With PWM**

Figure A.2 – Output voltage of a VSC phase unit for a 2-level converter

PWM is an established technique in converters for motor drives, but carries the disadvantage of much increased switching losses.

An alternative to PWM is to use a more complex converter with a higher number of output levels – a "multi-level converter". There are a number of 3-level or 5-level converter topologies available, but in a power system application these too will generally still require PWM in order to obtain sufficiently low harmonics.

However, there are some converter topologies that are capable of producing much higher numbers of output levels, such that even without using PWM, the output voltage waveform is highly sinusoidal and little or no filtering is required. Figure A.3 shows the output voltage of a 15-level converter, which can be seen to be reasonably sinusoidal. In practice, higher numbers of levels than 15 would normally be used for HVDC transmission applications.

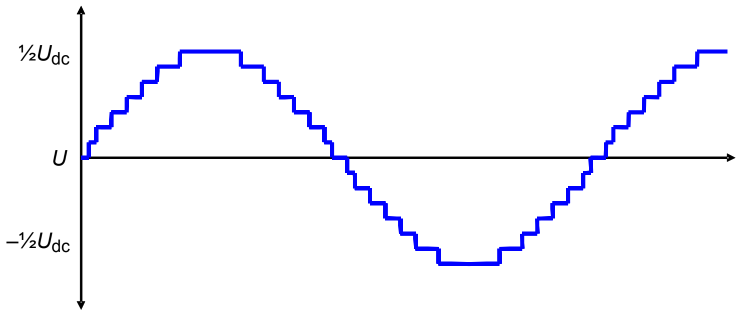

Figure A.3 – Output voltage of a VSC phase unit for a 15-level converter, without PWM

A.3 Overview of main types of VSC valve

Unlike conventional HVDC thyristor valves, which have evolved towards a largely common overall design, VSC valves are at an early stage in their technological evolution and exist in a number of forms.

At the time of writing of this standard, the VSC valves that are available commercially or have been described in literature fall into two basic categories.

- VSC valves of the “switch” type. These valves, like their thyristor counterparts, function only as a controllable switch, with only two permanent states: ON and OFF. In converters based on this topology, the d.c. capacitors are completely separated from the valves and can be tested in isolation.
- VSC valves of the “controllable voltage source” type. In valves of this type, the d.c. capacitors form an integral part of the valve and cannot be separated from it for testing purposes.

Certain type tests need to be performed in a quite different way depending on which of the above categories the valve falls into.

A.4 VSC valves of the “switch” type

A.4.1 General

VSC valves of this type bear a close apparent resemblance to conventional thyristor valves, in that they consist of a large number of series-connected IGBT devices which are switched simultaneously. As with conventional thyristor valves, simultaneous switching of the series-connected IGBTs is vital. Valves of this type are normally used with converters with a relatively low number of output levels.

To compensate for the low number of output levels, such converters usually use pulse width modulation (PWM) to achieve a good approximation of a sinusoidal output voltage.

Some of the more common converter topologies that can be used with this type of VSC valve are described below.

A.4.2 2-level converter

In this, the simplest type of VSC, each VSC phase unit comprises just two VSC valves connected in series and sharing an a.c. terminal. The two valves are switched alternately such that, at any given time, either one or the other valve is conducting, but never both. (In practice, there is usually a slight dead-time or “underlap” between the two valves).

The circuit topology of this converter is very simple (see Figure A.4) and requires very little explanation. When V1 is conducting, the a.c. terminal is connected to the upper d.c. terminal and therefore produces an output voltage of +½U_{dc}. When V2 is conducting, the a.c. terminal is connected to the lower d.c. terminal and therefore produces an output voltage of –½U_{dc}.

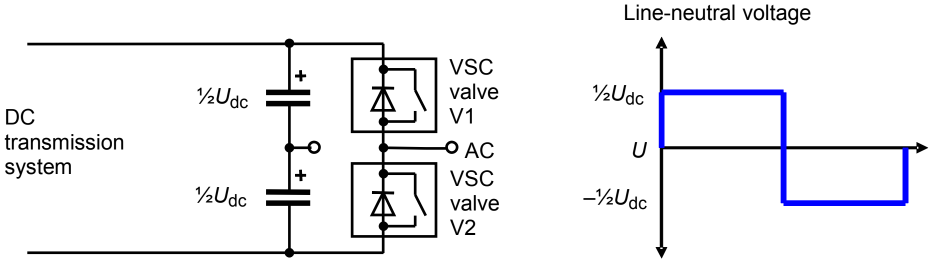

Figure A.4 – Basic circuit topology of one phase unit of a 2-level converter

A.4.3 Multi-level diode clamped converter

In this family of converters, the d.c. capacitor is sub-divided into a number of discrete stages connected in series, more than two IGBT valves are provided per phase unit and diode valves are used to connect between various intermediate points in the d.c. capacitor and in the phase unit.

In the simplest version of this circuit (see Figure A.5), the three-level converter, each phase unit contains four independent VSC valves connected in series. The d.c. capacitor is subdivided into two series-connected units (as it frequently is for a 2-level converter). The a.c. terminal is connected to the terminal between V2 and V3, and the ¼ and ¾ points (between valves V1/V2 and V3/V4) are connected to the d.c. midpoint via diode valves.

With this converter, three output states are possible from a single phase unit. When valves V1+V2 are conducting, the a.c. terminal is connected to the upper d.c. terminal and therefore produces an output voltage of +½U_{dc}. When valves V3+V4 are conducting, the a.c. terminal is connected to the lower d.c. terminal and therefore produces an output voltage of –½U_{dc}. When valves V2+V3 are conducting, the a.c. output voltage is “clamped” at the d.c. midpoint voltage by the diode valves.

The same principle can be extended to higher numbers of levels by further subdividing the d.c. capacitor and using more VSC and diode valves. In a 5-level converter, the d.c. capacitor is subdivided into four discrete stages, and there are eight VSC valves and six diode valves (see Figure A.6). In this circuit, the valves are switched in adjacent groups of four, for example V1+V2+V3+V4 gives an output voltage of +½U_{dc}, V2+V3+V4+V5 gives an output voltage of + ¼U_{dc}, etc.

It can be seen that as the number of output levels increases, the complexity of the circuit increases disproportionately. This is made worse by the fact that not only the number, but also the voltage rating of the diode valves increases rapidly with the number of output levels.

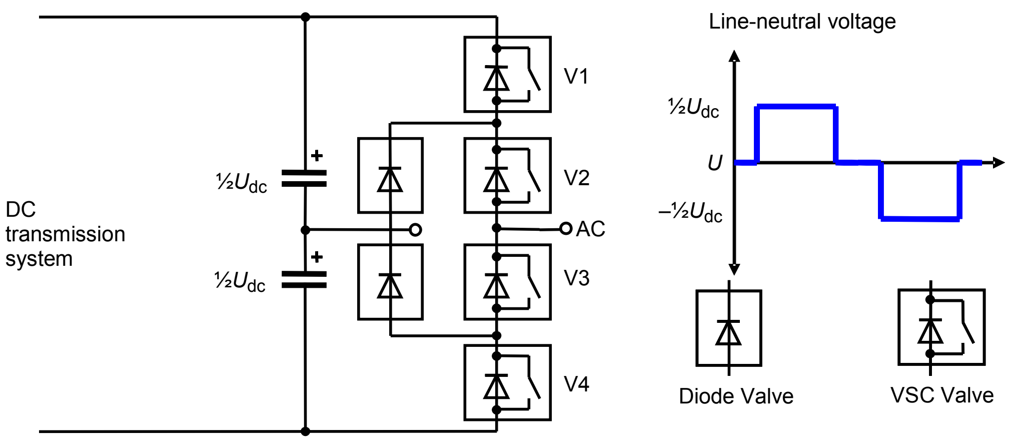

Figure A.5 – Basic circuit topology of one phase unit of a 3-level diode-clamped converter

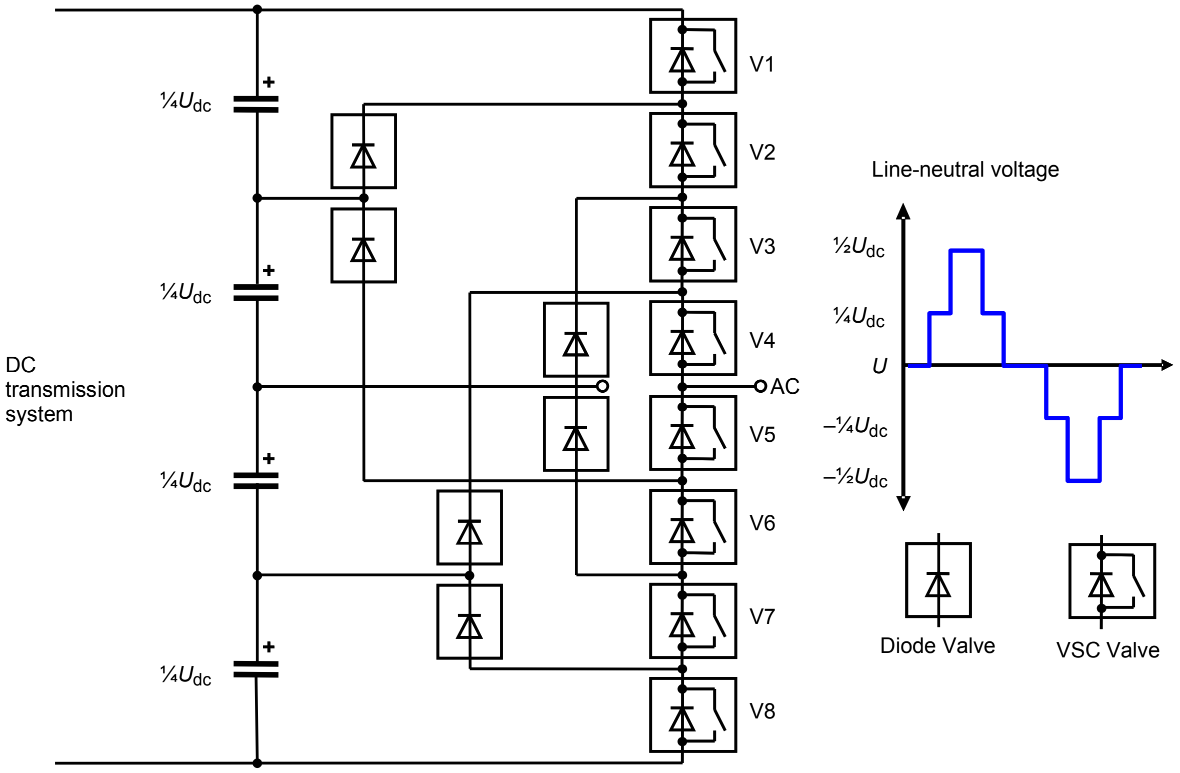

Figure A.6 – Basic circuit topology of one phase unit of a 5-level diode-clamped converter

A.4.4 Multi-level flying capacitor converter

This circuit achieves the same result as the diode-clamped converter by a different method. Instead of using diode valves to clamp the output voltage to one of the intermediate d.c. capacitor stages, it uses one or more additional d.c. capacitors, which are isolated from the d.c. terminals and hence “floating” or “flying”, to achieve the same effect. This circuit is sometimes also referred to as the “Foch-Meynard” circuit after its inventors.

The 3-level flying capacitor converter (see Figure A.7) has a single flying capacitor with a nominal voltage of ½U_{dc}. This capacitor is connected between the terminals shared by V1/V2 and those shared by V3/V4. As with the 3-level diode-clamped converter, valves are switched in pairs but the pattern to achieve zero output voltage is different. To achieve an output state of 0, either valves V1+V3 or valves V2+V4 are switched on. V2+V3 is an illegal combination as it would short-circuit the flying capacitor.

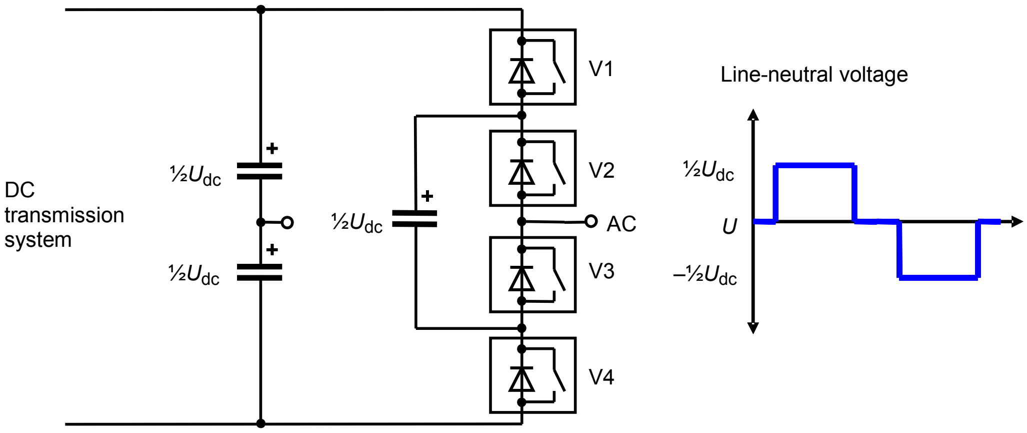

Figure A.7 – Basic circuit topology of one phase unit of a 3-level flying capacitor converter

The number of VSC valves per phase unit is the same for this converter as it is for a diode-clamped converter with the same number of output levels. Like the diode-clamped converter, higher numbers of output levels are possible, but at the expense of disproportionately increased complexity.

A.5 VSC valves of the “controllable voltage source” type

In the 2-level converter, the valves and d.c. capacitor are clearly separated items of equipment and can be designed and tested in isolation. However, as the number of output levels increases, it is seen from Subclause A.4.3 and A.4.4 that the d.c. capacitor(s) become increasing subdivided and the valves and d.c. capacitor become increasingly inter-dependent.

As the converter starts to approach the ideal, where the number of output levels is sufficient to obtain a good approximation to a sinusoidal waveform without using PWM, the subdivision of the d.c. capacitor and the interconnectivity between capacitors and IGBTs can become so complex that it is no longer practical to make a clear distinction between the two. In such cases, it may be more convenient to consider the “VSC valve” to be not simply the IGBT elements that perform the switching, but also the distributed d.c. capacitors. In effect, such a valve is no longer simply a switch but is now a controllable voltage source, connected between the a.c. terminal of the corresponding phase unit, and one of the d.c. terminals (see Figure A.8).

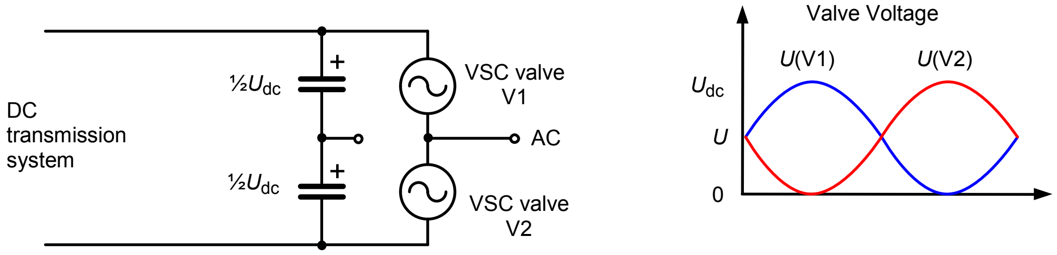

Figure A.8 – A single VSC phase unit with valves of the "controllable voltage source" type

Each of the valves V1 and V2 in the phase unit produces a unipolar output voltage approximating to a fully offset sinusoidal waveform with extremes of U=0 and U=Udc. The output voltages of the two valves are varied such that at any given time, U(V1) + U(V2) =U_{dc}.

In principle, there can be many different methods of implementing such a valve, but one such implementation is that shown in Figure A.9. This circuit is modular, each module comprising a single, isolated d.c. capacitor and two IGBT switches. In effect, this circuit is very similar to that of the basic 2-level converter (see Figure A.4) except that the interconnections between modules are made from the a.c. terminal (between IGBT1 and IGBT2) of one module, to one of the d.c. terminals of the neighbouring module. With this circuit, each module can produce two discrete output states: U=0 (obtained by switching IGBT2 on) or U=U_{dc_module} (obtained by switching IGBT1 on). U_{dc_module} is the d.c. link voltage of a single module, which is much less than Udc, the d.c. link voltage of the complete system.

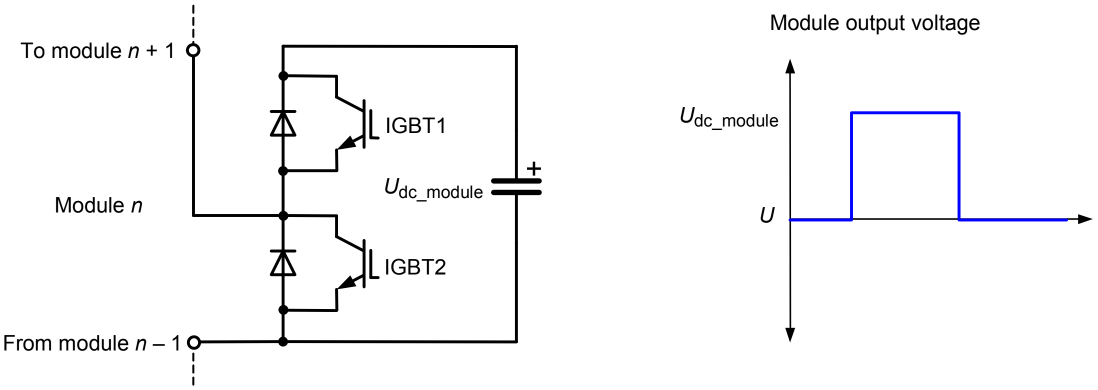

Figure A.9 – One possible implementation of a multi-level "voltage source" VSC valve

Since the circuit is inherently modular, it is relatively straightforward to obtain high numbers of output levels, without requiring either PWM (which leads to higher switching losses and requires filtering) or series-connected IGBTs (which leads to problems of ensuring voltage distribution). On the other hand, the number and size of discrete d.c. capacitors required can be considerable, and there may be difficulties in ensuring that all d.c. capacitor voltages remain balanced. In comparison with two- or three-level converters, therefore, this topology allows for a simpler valve design and lower losses at the expense of a more complex controls architecture and greater space requirement.

A.6 Main differences between VSC and conventional HVDC valves

VSC valves differ from conventional thyristor-based HVDC valves in many respects. It is important to appreciate these differences in order to understand the differences in approach that need to be taken when testing such valves.

Whilst there are a great many differences, the principal ones that affect valve testing are as follows.

- VSC valves are capable of both being turned ON and being turned OFF by control action. In contrast, conventional HVDC thyristor valves can only be turned ON by control action and, to achieve turn OFF, require the external circuit to force the current to zero and then apply a period of reverse voltage. Hence, tests to demonstrate minimum extinction angles or positive voltage transients during the recovery interval (which are so important for thyristor valves), have no significance for VSC valves.
- In VSC valves, the valve is not capable of supporting reverse voltage (because it contains in-built freewheel diodes), but can conduct reverse current. In conventional HVDC thyristor valves, the valve can withstand reverse voltage but not conduct reverse current.
- In VSC valves, protective turn-ON is generally not used because of the risk of creating a short-circuit across the d.c. capacitor, but instead protective turn-OFF is employed as a means of suppressing overcurrents. By contrast, in conventional HVDC thyristor valves, protective turn-ON is widely used and protective turn-OFF is not possible.
- The large d.c.-side capacitance means that there are few circumstances where a VSC phase unit can experience fast voltage transients between terminals. In valves of the “controllable voltage source” type (where some of the d.c. capacitance is embedded within the valve) the same is also true for voltages between the terminals of the valve.

Annex B
(informative)

Fault tolerance capability

Fault tolerance capability may be defined as the ability of an HVDC VSC valve to perform its intended function, until a scheduled shutdown, with faulted components or subsystems or overloaded components, and not lead to any unacceptable failure of other components, or extension of the damage due to the faulted condition. Special features may be required in the design to ensure fault tolerance. Examples of faults for which fault tolerance may be required are given below.

a) Short circuit of an IGBT or diode

   Even though a short-circuit IGBT or diode will shunt the other components at the valve level, in some designs there may be a danger of overloading gate driving circuits, overload of current connections (where parallel IGBT or diode are used), or changes in clamping load.

b) Missing of on-gate at one valve level due to loss of normal on-gate pulses to that level

   Missing of on-gate leads to parallel overvoltage of the components at the affected level.

c) Insulation failure of a snubber capacitor, snubber resistor or other components if applicable

   Insulation failure of any component in parallel with the IGBTs or diodes can attract load current into it, leading to a hazardous condition.

d) Leakage of small quantities of valve coolant

   If the valve is liquid cooled, small leaks may not be easily detected. Escaped coolant can contaminate sensitive components, leading to malfunction, and can increase the probability of insulation failure.

The purchaser should review the design offered with the supplier to determine the probability and likely consequences of certain failures. Where appropriate, consideration should be given, in the type test programme, to the performance of special tests to verify critical aspects of the fault tolerance capability of the valve. The details of such tests are subject to agreement on a case-by-case basis.

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